HIGH ENERGY DENSITY CAPACITOR TESTING FOR THE AFWL SHIVA

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Introduction and Summary

The introduction of inductive storage/opening switch pulse forming networks as an operational reality in the multi-megajoule, sub-microsecond range, makes possible the design and operation of very large high power systems at modest cost.[1,2] The operational simplicity and economy of the pulse shortening system shifts the emphasis from opening switches to that of finding suitably simple, highly reliable, economical prime energy sources which are practical at levels of 10 MJ and higher. While the AFWL is currently exploring both explosive and rotating primary stores, capacitive stores represent the most practical primary energy source for meeting the AFWL's near term operational requirements.

The "SHIVA II Prime" upgrade consists of replacing the existing 3.3 kJ, 1.85 μF capacitors with "plug-in" higher energy density capacitors. Based on capacitor development work by manufacturers it appears that a nominal 6 μF, 60 kV capacitor in an 11" x 14" can is near the limits of current technology. Using the 6 μF, 10.8 kJ capacitor results in a factor of 3 increase in stored energy at no increase in operational voltage. The equivalent system capacitance will then be 864 μF at 120 kV ($\pm$ 60 kV) or 6.22 MJ. The best testing technique is one which duplicates, as nearly as reasonable, the actual parameters the capacitors would see in the full-scale system.

Lifetime testing and analysis of small samples of high energy density (HED) discharge capacitors at the AFWL were conducted to find a component suitable for upgrading the SHIVA capacitor bank to a 6 MJ facility. Evaluation was performed with discharge conditions of approximately 250 kA per capacitor at 60-70% reversal and < 2 μs quarter period. Dielectric systems including Kraft paper with caster oil impregnant and Kraft paper, polypropylene with DiOctyl Phthalate (DOP) impregnant were tested.

Based on the test results of the 6 μF, 60 kV capacitors, one dielectric system marginally met the minimum lifetime criteria demonstrating a Weibull beta of 2.02 and a mean time to failure of 6752 shots. Other dielectric systems failed in such a way as to make their use in SHIVA undesirable with respect to overall life cycle costs, high probability of early catastrophic failure and collateral system damage, and expensive acceptance testing to eliminate units that are subject to premature failure mechanisms. Actual application in the large parallel capacitor bank will be less demanding than the testing conditions (high reversals, slow charging, ringing discharge, etc.), and the selected unit should fare considerably better. The results indicate that special attention to current carrying elements of the capacitor, especially the foil/buss solder connection and the center electrode construction, is needed.

Testing Apparatus and Method

The testing apparatus developed for evaluating the capacitors consists of two HED cans in parallel driving a transmission line through a single gas switch and a low inductance, low impedance load. See Figure 1. As many as eight of these modules were charged and

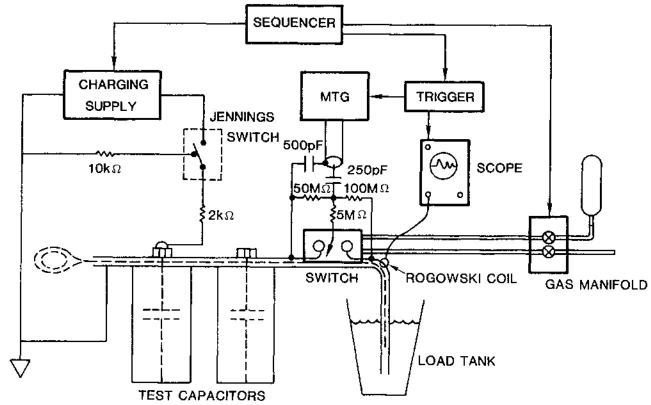

Figure 1. Capacitor life test arrangement.

operated together to accumulate simultaneous data on up to 16 capacitors. Testing was interrupted only by routine maintenance, end of duty day, or a capacitor failure. For the latter situation, the failed unit was promptly replaced with a new or partially tested capacitor, and the testing was resumed while a post-mortem inspection of the failure took place. A randomly selected number of units from each sample batch were tested in the charge-discharge mode. Tests continued until sufficient failure data were accumulated to parameterize the unit's lifetime distribution function, or until adequate confidence was obtained that the units would meet the minimum system lifetime specifications.

Constant current charging was achieved with a 300 mA, 60 kV power supply with charging times limited to about 20 seconds with a motor driven variable auto transformer. Filling and partial venting of the sulfur-hexafluoride and argon gas mixture in the rail gap switches was done between each shot. Typical switch operating pressures were 50 to 60 psig, and the flush-fill process took about 30 seconds. The time between shots is a about one minute, depending on the total capacitance to be charged. The rail gap switches are a three electrode field-distortion geometry driven by a master trigger generator (MTG). The discharge current of > 500 kA is near the rated limit of the existing rail gap switches, which are the same type employed on SHIVA. An automatic sequencer unit was designed and built to control the charging, gas transfer, and triggering systems such that an operator was needed only to monitor the repetitive operation and be prepared to shut down the complex when necessary.

The testing module load consisted of parallel flat plates immersed in a saturated solution of ammonium chloride with separation and area adjusted for 50 to 60 mΩ in order to maintain the ringing reversals at 65 to 70%. Typical Rogowski coil data of the discharges demonstrated quarter periods of 1.7 μs indicating a 98 nH module.

The testing apparatus performed reliably with routine maintenance required for such tasks as switch clean-up and replacement, load tank liquid level adjustment and mixing, checking the torques on the capacitor compression ring header plates, etc. Switch failure every few thousand shots was a major expense throughout the testing. The dominant failure mode was the fracture of a machined acrylic cover, resulting in mechanical

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damage to the cast epoxy base. The mortality rate was reduced somewhat by minimizing the operating gas pressure and by cleaning regularly; however, the 0.7 C high reversal repeated stresses still took their toll.

All the capacitors were treated identically; there was no failure correlation with position in the modules. Every unit was allowed 48 hours to stabilize to the laboratory environment. A few lower voltage warm-up shots were applied. Very rarely, a bogus failure occurred due to tracking over the plastic compression donut (see Figure 2) used for the high voltage seal between the capacitor center electrode and the transmission line plates. This problem was reduced by regular torque surveillance and the use of dielectric oil and paper to improve the seal. All such failures were discounted with respect to the lifetime statistics. It is interesting to note that in 90% of the bonafide failures the 20 kJ available from the module pair was contained within the steel capacitor housings. The breakdown manifested itself in the form of a lump or some other can deformity accompanied by a characteristic noise. Careful observation indicated that the dielectric breakdown often initiated at a foil edge where the electric field stresses are the highest and were aggravated by wrinkles, gas bubble formation, chemical processes, etc. Upon the initial failure, subsequent series capacitors within the same pad were then overvolted and would, in turn, short out.

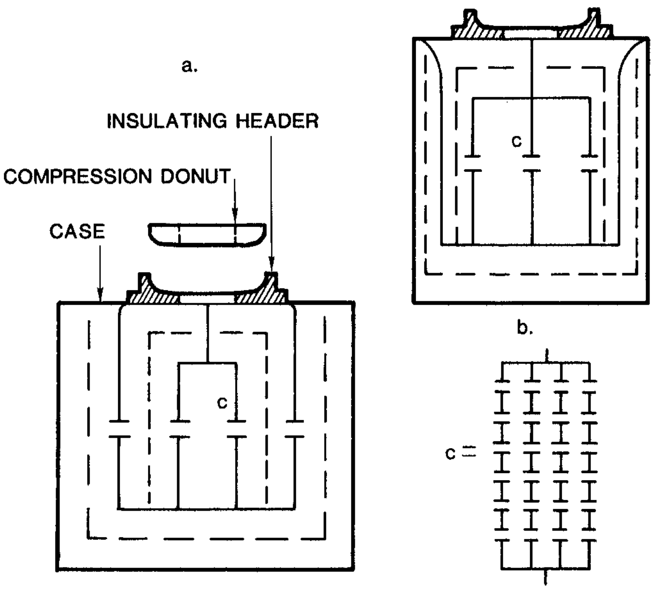

Figure 2. a. Down-and-up capacitor design.
b. Parallel pad capacitor design.

Dielectric System Performance

The technical requirements are a combination of what is normally specified for HED capacitors and those constraints necessary to make them compatible with the SHIVA hardware and electrical systems. They must be capable of constant current charging to the rated voltage and discharging with system frequencies of about 1 MHz. The acceptable lifetime specification had to be determined by the AFWL. It is common within the industry to predict the lifetime performance of new capacitor designs by relating some of their fundamental parameters to those of well known and established units with expressions like the following:[3]

$$L' = L \left(\frac{E'}{E}\right)^{-3.5} \left(\frac{V'}{V}\right)^{-4} \left(\frac{Q'}{Q}\right)^{-1.6} \qquad (1)$$

Equation (1) can be used to estimate a shot life for the new HED model with respect to the standard 1.85 μF discharge capacitor, which has a lifetime of L = 60,000 shots. The dielectric stress, E, of the 1.85 μF (6 μF) unit is 2083 (3333) V/mil; the section voltage V, is 7500 V for an eight section pad (10,000 V for a six section pad); and the equivalent ringing circuit quality factor, Q, is approximately 9.67 at 85% reversal (4.40 at 70% reversal). The resulting L' = 12,913 shots is considerably less than the 60,000 shots for 50% failure of the 1.85 μF unit, but it serves as a guideline against which to compare the test sample results. Based upon work performed by E. Kemp and G. Boicourt of LANL[4,5] and upon data collected by the capacitor manufacturers,[3,6,7] the practice of describing capacitor lifetime data as Weibull distributed is continued here.

The capacitors evaluated can be separated into two main categories according to their dielectric system: 1) castor oil (CO) and Kraft paper (up to 3333 V/mil), and 2) dioctyl phthalate (DOP), paper, and polypropylene (up to 4500 V/mil). The impregnants contained other additives and scavengers to help absorb water vapor and other undesirable contaminants. The Kraft paper dielectric of approximately 0.00035 inch thick sheets in nominal densities of 1 to 1.2 gm/cc is a relatively standard item. The polypropylene capacitor grade film is typically 0.0006 inch thick sheets. The other major design categories for comparison include:

1. All parallel pads with return ground strap to top of housing (DOP and CO). Refer to Figure 2b.
   a. Twelve pads, six sections/pad.
   b. Twelve pads, seven sections/pad.
2. Down-and-up (D&U) design, two parallel packages of four pads (six sections/pad) in parallel which are in series with eight more pads in parallel (CO only). Refer to Figure 2a.

Other important considerations for interpreting the results involve the actual test conditions and the previous treatment of the capacitor samples. Table I briefly summarizes the performance of the various dielectric systems. The "FINAL SHOT" column represents the shot number of the last failure, unless otherwise noted. The following discussion elaborates a bit more on the results.

TABLE I

Testing Results

Impregnant	Pad Design	C(μF)	Sample Size	Failures	Final Shot	Remarks
DOP	Parallel	6.45	6	3	434	Compression header
DOP	Parallel	6.06	13	4	732	All open
DOP	Parallel	6.10	8	5	1359	Rebuilt
DOP	Parallel	7.40	8	3	536	1 shorted
DOP	Parallel	7.45	5	4	4283	Rebuilt
DOP	Parallel	6.0	6	4	1724	High current electrode
DOP*	Parallel	6.2	13	5	1038	*Different vendor
C O	Parallel	6.2	8	0	1895	Original prestressed
C O	Parallel	6.2	8	6	2165	Original unstressed
C O	Parallel	6.0	8	3	1243	Unconditioned
C O	Parallel	6.0	8	3	1458	Conditioned
C O	Parallel*	5.95	6	3	1973	*7-sections/pad
C O	D&U	6.04	9	4	4970*	*Some to 10,000
C O	D&U*	6.15	7	4	7688	*Alternating foils

6.45 μF DOP

Six of the 6.45 μF DOP capacitors were tested to 434 shots. At this point, three of the units were found to have cracked header insulators, of which two were leaking impregnant. The headers had been designed for compression applied to the center terminal, while the gasket approach employed in the test had applied tension to that terminal. Opening the failed cans

revealed that arcing at the contact points, where the ground straps were brazed to the lip of the can, may have caused a gas build-up inside the unit to crack the headers. Internal inspection showed some dielectric damage, although none of the capacitors had failed at 434 shots.

6.06 and 7.40 μF DOP

Thirteen of the 6.06 μF DOP capacitors were tested until four failed, and eight of the 7.40 μF DOP capacitors were tested until three failed. Of all the failures, only one of the 7.4 μF cans shorted completely; the others failed open in the sense that they were discovered to be leaking oil through cracked header insulators or ripped case weld seams. Internal inspection revealed arcing between the return ground straps and the outer case where part of the paper insulation was missing, probably resulting in a build-up of gas pressure. The accumulating bubbles likely encourage more arcing near the top of the capacitor leading eventually to the failures.

6.10 and 7.45 μF DOP

The unfailed and untested capacitors from the lots discussed in the previous paragraph were "rebuilt" by the vendor who inserted a heavy, wider, ground insulator into the package. The units returned with a slightly higher capacitance and are identified in Table I, as the 6.10 and 7.45 μF samples respectively. Both performed significantly better. Figure 3 contains the Weibull plot for the 6.10 μF sample (parallel pad DOP). The mean-times-to-failure (MTTF) were about 917 and 1633 shots, and the rather low Betas (the Weibull distribution shape parameter) were approximately 1.2 and 0.64. Samples displaying $\beta < 1$ come from a family in which the probability of failure decreases with increasing life (infant failure). This suggests that extensive "break-in" may eliminate weak members of the population. The failure mode appeared to be the typical edge margin breakdown, giving rise to bulk dielectric damage. Those "rebuilt" units that had been previously tested with some ground strap arcing were essentially indistinguishable from the untested "rebuilt" units (at least with these small samples of 8 and 5, respectively). What is not understood is whether these dielectric systems would have performed considerably better if they had not required the rebuilding process and the accompanying risks of trapping gas bubbles.

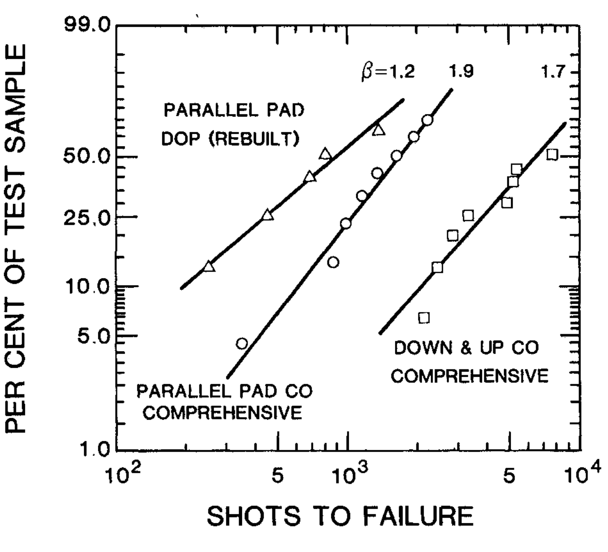

Figure 3. Weibull plot of three samples.

6.0 μF DOP

Another set of the 6.0 μF DOP capacitors, similar to those already tested, was built using a modified center electrode that should carry the high current densities better without burning at contact points, which had been observed earlier. Six units were tested until four failed. No marked improvement was found, but this was probably due to arcing where the ground strap paper insulation was again discovered to be inadequate.

6.2 μF DOP

The 6.2 μF DOP capacitors were provided for testing by a different vendor. Five failures at shot numbers 5, 102, 139, 594, and 1038 resulted from a sample of 13. Ground strap to case arcing was discovered in these cans, although the failure mechanism did appear to be the dielectric medium breaking down before gases due to the arcing could develop to any large extent.

6.2 μF CO

The 6.2 μF castor oil capacitors were the first ones tested, and therefore, underwent a slightly different test procedure than the other capacitors, since a somewhat lengthy period of time was spent testing the apparatus and developing a load at lower voltages. One set of eight cans, referred to as "original pre-stressed", experienced more than 45 shots at 30 kV, six at 40 kV, nine at 50 kV, and 96 at 60 kV prior to beginning the routine testing, which took the set up to 1895 shots with no failures. On the other hand, eight of the "original unstressed" 6.2 μF castor oil capacitors were tested to 2165 shots with six failures occurring in this sample. They belonged to the same family as the earlier set with the exception of two months extra aging time.

6.0 μF CO

Eight of the 6.0 μF castor oil sample were tested to 1243 shots accuring three authentic failures. To compare any failure tendancies to the results in the above paragraph, a set of eight "conditioned" 6.0 μF capacitors were prepared by putting 15 hours of 40 kV high-pot on them, plus 500 shots each at 40 kV and 50 kV. The 60 kV testing continued through 1458 shots and 3 failures. The performance was obviously not improved significantly by conditioning and lends no statistically acceptable explanation for the previous difference.

5.95 μF CO

The 5.95 μF castor oil sample was tested as a lower stress alternative. Instead of the usual six section pads (10 kV section to section stress), the parallel pads in this unit consisted of seven series sections (8.6 kV stress). The failure rate did not improve meaningfully, however; three out of six shorted by 1973 shots. The three separate parallel pad castor oil designs resulted in Weibull representations so similar that a Weibull plot of β = 1.9 in Figure 3 shows their comprehensive or total performance.

6.04 μF CO

A longer-lived higher inductance (~ 40 nH) capacitor evolved in the form of the 6.04 μF castor oil down-and-up pad design. The fourth failure of the sample of 9 units went at 4970 shots while some were tested all the way to 10,000 shots without failing. The Weibull statistics indicate an MTTF of 5014 shots. This pad arrangement involves pumping the same currents through fewer pads and, hence, higher current densities. Inspection of the dissected cans showed serious

"burning" damage to the solder swaged contact joints at both ends of the pads, but primarily located at the bottom of the can (half-voltage point) where the current must make a sharp "U-turn". The burning/arcing at the foil joints was thought responsible for leading to eventual failures.

6.15 μF CO

An improved version of the down-and-up design was tested. An "alternating foil" arrangement was chosen such that different gauge aluminum was placed in the package with the heavier foils being used to form the tabs at both ends of the pads. The result was a substantial reduction in the swaging damage. Testing seven of these 6.15 μF castor oil capacitors found the fourth failure at 7688 shots. The statistics yield the highest beta (2.02) and MTTF (6752) yet observed. One unit not included in this data had a severe folding crease within one pad which caused the capacitor to fail at the first 60 kV discharge although it had lasted through 100 shots at 40 kV and 200 shots at 50 kV. Such contributors to the statistical "infant mortality" should be weeded out with quality control and full energy discharge tests by the manufacturer. All the legitimate failures showed damage at the middle of the pads due to higher electric field stress where the margin spacing was as much as 15% narrower than the other margins throughout the pad. The combined failure data of all the down-and-up castor oil capacitors are shown on the Weibull plot of Figure 3. Upon close observation one is inclined to describe the data as two different families, but that conclusion is not supported by such small samples.

By extrapolating the same comprehensive down-and-up CO failure data as done in Figure 4, 90% confidence limits may be constructed for different sample sizes. Future samples that are tested in a similar fashion may or may not represent the same population of capacitors depending on where they fall within these limits. If the family described by the best performing units in this effort does extrapolate as shown, then the 90% confidence interval for the full 576 capacitor SHIVA bank indicates that the first failure will occur at approximately 50 shots which is marginally acceptable for AFWL needs.

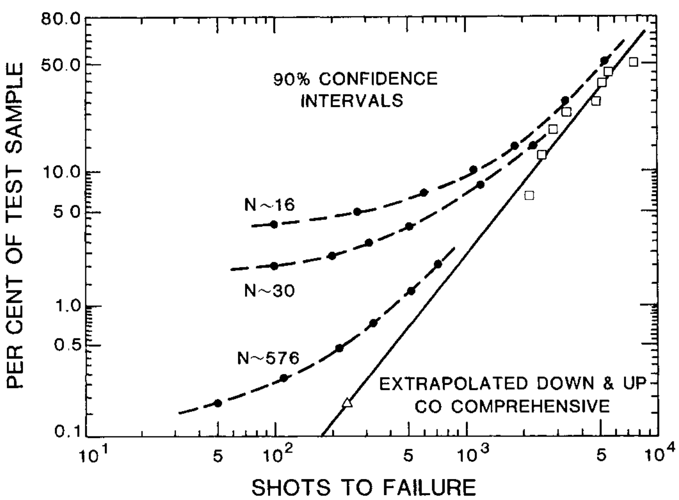

Figure 4. Confidence limits of expanded Weibull plot.

Conclusions and Recommendations

The castor oil capacitor undoubtedly fared better throughout the testing, especially the down-and-up pad design. Only tentative conclusions can be made on the DOP samples. Most of those failures likely resulted from assembly errors (insufficient ground strap insulation, etc.), and may not be valid data for evaluating the dielectric systems of interest. Unfortunately the entire package within the steel containers had to be tested together as a unit and evaluated accordingly.

The best 50% failure data have indicated a MTTF of less than 7000 shots, but with a sufficiently high β to make that sample marginally acceptable for the SHIVA system applications. This performance can be "folded" upwards (due to the worst-case testing conditions) to more closely resemble the previous estimate of 12,913 shots. This leads to expectations of a better performing capacitor under actual operating conditions and vendor quality control. Inspections of the failed units support statements that the lifetime dependence upon stress results from corona and dielectric surface tracking with occasional bulk breakdown, and the effect can be significantly improved through pulse charging.[8]

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